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METHANE-FUELED PROPULSION SYSTEMS

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Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Second Joint Propulsion Specialist Conference sponsored by the American Institute of Aeronautics and Astronautics
Colorado Springs, Colorado, June 13-17, 1966

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ABSTRACT

Liquid methane fuel is superior to JP or kerosene in terms of heating value, cooling capacity, and (possibly) in cost and availability. When it is applied to the difficult commercial supersonic transport mission, it is estimated that the payload capacity can be increased by about 30 percent and the direct operating cost reduced a like amount. Because methane is a good thermodynamic working fluid, there exists the possibility of making further gains in aircraft performance by employing special engine cycles. The cryogenic nature of liquid methane poses unusual problems in handling, storage, and engine and airframe design. However, the magnitude of the potential gains warrants further analysis and experimental work to substantiate the merits of the concept.

INTRODUCTION

Aircraft operators are always desirous of improving the range, payload, and economy of their vehicles. However, the achieving of satisfactory levels of these attributes for future supersonic airplanes appears to be especially difficult in comparison with current and proposed subsonic planes. Although continued advances in engines and airframes will gradually alleviate the present limitations, the performance of such vehicles as the proposed supersonic transport could well benefit from some more striking type of gain. The intent of this paper is to point out that such a major gain is potentially available through the use of a new fuel - liquid methane.

The use of unconventional fuels is not a new concept. A number of them, including methane (see, e.g., Ref. 1), were seriously considered more than 10 years ago, the primary interest then being military applications. More recently, it was realized that this approach might have merit in the commercial supersonic transport and other future vehicles. The data in this paper are abstracted from studies initiated by the Lewis Mission Analysis Branch in late 1964 and continued since then with the aid of numerous consultants from other Lewis groups.

Although many varieties of aircraft could benefit from the use of methane, its advantages will be illustrated herein in terms of a representative SST configuration. Some special engine cycles that utilize the peculiar physical and thermodynamic properties of methane are also presented.

CHARACTERISTICS OF METHANE

The major desirable attributes of a fuel include high heat of combustion, high density, ready availability and low cost, high heat-sink capacity, good storability and handling, etc. The suitability of liquid methane in terms of these qualities is examined in this section.

Basic Properties

Table I compares some of the important characteristics of methane with those of ordinary jet fuel. For perspective, a number of other fluids are also included. The prime reason for interest in methane lies in its heat of combustion, 16 percent higher than JP or kerosene. After accounting for the energy removed when the methane is liquefied, the advantage over JP is about 13 percent. Everything else being equal, this should result in a 13-percent increase in engine specific impulse and a similar increase in range. Methane is the best of the light hydrocarbons in this regard due to its high hydrogen content (chemical formula, CH_4). Pure hydrogen is better yet, but is unattractive due to its high cost, low density, and extremely low boiling temperature.

Methane can also be expected to cause problems due to its cryogenic nature. Special handling and tank insulation are required because of methane's low boiling point. The low density (about half that of JP fuel) could lead to tank volume difficulties on the airplane. As a compensation, however, the comparative freedom from decomposition at high temperatures and the initial low tank temperature give methane a very high heat-sink capacity, six times that of JP; this can be very significant for supersonic applications. Other pertinent properties of methane are listed in Table II.

Economic Aspects

Availability. - The major commercial source for methane is from natural gas. The gas composition is quite variable, but methane is always the major constitutent (50 to 95 percent). Other light hydrocarbons such as ethane, propane, butane, etc., (5-40 percent) are usually present that have definite commercial value. The remaining 0 to 10 percent is composed of CO_2, N_2, He, H_2O, H_2S. It is desirable to employ only rather pure methane as the fuel in an airplane so as not to penalize the heating value. However, the inclusion of 10 percent ethane in the methane reduces the heating value by only 1/2 percent. It is believed that this type of mixture can be easily prepared from most natural gases.

Natural gas is quite abundant throughout most of the world (Table III). The estimated consumption of an SST fleet is probably less than 10 percent of the current production. Some areas of the world, however, are poorly supplied with this natural resource. Roughly speaking, the ultimate reserves of natural gas are comparable with petroleum. In fact, since only a small part of crude oil can readily be converted to jet fuels, it is possible that the long-term availability of methane will be greater than that of JP fuel or kerosene.

In any event, major airports are not located adjacent to gas fields, so that a transportation system is required to get the fuel from the well-head to the airport. Also, somewhere in the transportation line, a liquefaction plant must be provided to separate and liquefy the methane for use by the aircraft.

Transportation systems. - Various distribution techniques are schematically indicated in Fig. 1. They utilize different combinations of pipelines, rail, truck, or ship delivery and various locations for the liquefaction plant. There will generally be more than one feasible technique for supplying a given airport. A detailed analysis will generally be required to select the least costly techniques on a case-by-case basis.

When the terrain is favorable, the cheapest transportation method is pipeline delivery of gas. The preferred technique is thus the one illustrated at the top of the figure, with a pipeline running from the well directly to a liquefying plant located at the airport. (A number of such plants are now operated by gas companies for peak-shaving purposes.) At an airport, the liquid methane would be stored and then piped or trucked to the aircraft.

When this technique is not feasible, it will be necessary to liquefy the gas at some intermediate point (in order to reduce its volume by a factor of about 600) and then transport it in cryogenic containers. For long distances and/or over water, the use of specially constructed ships is practical and fairly inexpensive.[2] Liquefied natural gas is presently being carried in this manner from Algeria to England and from Libya to Japan.

If the destination seaport is near the airfield, it may be possible to pipe the liquid directly. In most cases, however, transfer to trucks or railcars (holding from 10 to 30,000 gallons) will be necessary. An alternative would be to gasify the fuel, deliver it to a distant airport via pipeline, and reliquefy it there.

Fuel cost. - The cost of liquid methane as delivered to the airplane will vary with the price paid initially for the gas, the transportation technique, the liquefaction method, the aircraft fueling procedure, etc. These factors have not been studied sufficiently to arrive at overall costs with any degree of certainty. Some representative numbers are discussed in this section, however, in order to give an indication of possible costs.

As shown in the following listing, the cost of natural gas at the wellhead is fairly low.

Well-head price, cents/thousand cu ft:	
Flare gas	1.5
Sahara	10 to 15
U. S. A.	25
Liquefaction plant at airport (10×10^6 lb/day):	
Gas at 40 cents per thousand cubic feet, cents/lb	0.94
Fixed charges at 12 percent, cents/lb	0.13
Operating cost, cents/lb	0.14
Total, cents/lb	1.21
cents/gal	4.2

The lower part of the listing presents a rough estimate of the cost of liquid methane based on the preferred technique of delivering natural gas via pipeline to a liquefaction plant located at the airport (Fig. 2). These estimates were prepared by the Institute of Gas Technology and are for a fairly busy airport serving 50 SST flights per day.

The cost of the raw material, that is, the natural gas at the end of the pipeline, is seen to constitute the major part of the cost. Amortization and operating expenses of the plant, whose capital investment would be about $45 million, is comparatively small. The resulting cost of 1.21 cents per pound (or 56 cents/million Btu) may be compared with a typical price of 1.8 cents per pound for kerosene (or 97 cents/million Btu).

This cost estimate is felt to be reasonable for major airports within the continental United States. In other localities not within reach of pipelines, the cost is apt to be considerably higher. For example, the present cost of liquefied natural gas delivered to an English seaport is 1.65 cents per pound. Depending on the technique employed to transport the methane from the ship to the airport, the cost would range upward from this value to perhaps 2 or more cents per pound.

AIRPLANE PERFORMANCE

In order to illustrate the benefits offered by the use of methane, a high-speed computer was used to generate engine performance data with that fuel, design a family of supersonic airplanes incorporating those engines, and calculate the capability and operating efficiency of the airplanes when flown through a typical flight. These results are then compared with reference airplanes using JP fuel. A cruise Mach number of

3 was used in all cases. (A more detailed discussion of the engine and airplane calculations is given in Ref. 3).

Basic Assumptions

Engines. - Afterburning turbojet engines were assumed for both fuels. Other engine types, such as duct-burning turbofans, would not be expected to affect the comparisons significantly. Typical Mach-3 performance is shown in Fig. 3. If the nominal turbine inlet temperature is kept at 2200° F (and all other design characteristics such as pressure ratios and efficiencies remain constant), the specific impulse increases by about 12 to 14 percent by switching to methane. The improvement is not identical to the 13-percent increase in heating value due to differences in the composition of the combustion products.

As discussed in a later section, the extra cooling capacity of methane can be utilized to increase the turbine-inlet gas temperature. A reasonable estimate of an achievable value is 2800° F. As indicated in Fig. 3, this higher temperature yields a further improvement in specific impulse at the maximum afterburning condition. The figure shows no improvement in the nonafterburning case due to the compressor pressure ratio being held fixed in this example. Note, however, that the maximum dry thrust is greatly increased. Although not apparent from the figure, this can ultimately result in a significantly lighter engine.

Airframe. - The configurations studied herein are based on the SCAT-15F vehicle, designed by the NASA Langley Research Center (Fig. 4). This configuration was selected as a representative SST design for which data were available; it is not claimed that it is necessarily the best. It should be recognized that the advantages of methane over JP fuel could be influenced by the airframe type. For example, a vehicle with high wing loading would have less volume available within the wings to store the low-density methane than would a low wing-loading vehicle like the SCAT 15F. (A wing loading of 50 lb/sq ft was used in the present analysis.) When necessary, of course, the fuselage can be extended to provide additional volume, but this causes weight and drag penalties. When required, these fuselage changes as well as those associated with changing the number of passengers have been included in the present study.

The fuel tank locations for the JP- and methane-fueled versions of the airplanes studied are indicated in Fig. 5. Adequate fuel volume was generally available for the configuration studied, even after accounting for unavailable space in the wing due to excessively thin sections, wheel wells, flaps, etc.

Mission. - The relative performance of methane- and JP-fueled supersonic transports was studied by considering hypothetical families of vehicles, each designed to accomplish the nominal mission specified as follows:

Cruise Mach number	3.0
Range, n. mi.	3500
Gross weight, lb	460,000
Maximum sonic boom, lb/sq ft:	
Climb	2.0
Cruise	1.5

With speed, range, and takeoff gross weight held fixed, improvements in airframes, engines or fuel are evidenced as increases in the passenger-carrying capacity of the aircraft. Associated changes in component weights and drags are accounted for, and the flight path incorporates appropriate operational constraints, such as maximum sonic-boom overpressure, takeoff speed, etc.

Flight Capability

Payload. - The left bar of Fig. 6 represents the passenger capacity, 198, of the reference JP-fueled airplane flying the nominal mission. The middle bar shows that the use of methane, with the same turbine-inlet temperature, yields an increase of 34 passengers, or 17 percent. If, in addition, the greater cooling capacity of methane is employed to raise the turbine-inlet temperature to 2800° F, the right bar indicates a passenger capacity of 259, for a total gain of 31 percent compared with the JP-fueled vehicle. Re-optimization of the compressor pressure ratio would yield on additional 2-percent gain. (The indicated benefits of high turbine-inlet temperature are probably representative, but it must be acknowledged that the ramifications of engine noise limitations in the vicinity of the airport need further exploration.)

Direct operating cost. - To the commercial operator, a more interesting criterion of airplane performance is the profitability. A good indication of this factor is the direct operating cost (D.O.C.), which includes the expense of flying the airplane plus maintenance and depreciation of the airplane and engines. As shown in Fig. 7, the lower D.O.C. with methane fuel reflects the improvement in passenger capacity, the reduction being in the order of 25 to 35 percent, depending on fuel costs. (A superiority in D.O.C. is calculated for all methane costs less than 3 cents/lb).

In the previous figures it was assumed that, if the technology of turbine cooling allowed 2200° F with JP fuel, comparable technology would allow 2800° F with methane fuel. It might be claimed, however, that the technology for 2200° F gas temperatures is not yet at hand for commercial JP-fueled engines. This gas temperature is high enough to require use of a cooled turbine. Currently proposed blade designs typically require bleeding about 10 percent of the compressor discharge air through the cooling passages, and result in a blade metal temperature of about 1700° to 1800° F. Such a metal temperature if considerably above those at which present commercial subsonic jet engines operate. Consequently, there is reason for concern about the reliability and lifetime of the high-temperature designs.

An alternative way in which to utilize the good heat-sink capacity of methane is to retain the reference 2200° F gas temperature, which then permits cooling the blades to a more modest metal temperature of about 1500° F. As shown in Fig. 8, this results in a passenger capacity of 232 and values of D.O.C. between 0.80 and 0.93 cent/seat mile.

A JP-fueled engine of comparable reliability (i.e., similar metal temperatures) must have its turbine-inlet temperature reduced to 1900° F or lower, with a resultant D.O.C. of 1.29 cents/seat mile. On this basis of comparison, methane again yields cost reductions of the order of 30 percent.

Component Technology

The indicated benefits of methane can be realized only if the many problems associated with the use of such an unconventional fuel can be successfully dealt with. This section discusses a number of these problem areas. (Major contributions to the information presented herein were made by J. B. Esgar, R. R. Hibbard, I. I. Pinkel, and H. H. Valentine of Lewis.)

Fuel system. - Obviously, there must be changes in such components as fuel pumps, lines, and controls when a cryogenic fuel is employed. Some of the other considerations that arise are introduced by reference to the typical flight path illustrated in Fig. 9. Various critical points during the flight are indicated.

During ground hold before takeoff, one must contend with heat leaks into the tanks, that tend to boil away some of the fuel. This can be minimized by insulating the tanks and/or by subcooling the methane before loading it on the airplane. Another ground problem will be the tendency for atmospheric moisture to condense and freeze on the cold external wing surfaces. Insulation will again help, but special blankets or heated wing surfaces may be needed under adverse weather conditions. After takeoff, the wing temperature will increase so that in-flight icing should be no more severe than it is for current aircraft.

A serious problem occurs as the airplane gains altitude from the ground to about 30,000 feet. During this time, the ambient pressure drops by 10 psi. Since the methane, loaded at 1 atmosphere and -259° F, is a boiling liquid, a large amount of fuel (about 10 percent) would be flashed off as vapor and lost if the fuel tanks were simply vented to the atmosphere. This loss would be intolerable. Being solely a consequence of the reduced tank pressure, insulation would not affect this boiloff. However, other approaches are conceivable.

One approach is to utilize the vaporized fuel in some beneficial fashion, that is, in the engine. Although the rate of boiloff in some portions of the flight may exceed the total engine fuel requirement, careful shaping of the flight path can minimize this discrepancy. The main difficulty with this approach would be the weight penalty associated with the gas compressor required to inject the vapor into the combustor and the complexity of the dual fuel system.

An alternative approach is to attempt to limit the methane from boiling off in the first place. The most direct approach would be to seal the tanks and not permit the fuel pressure to drop. This would, indeed, eliminate the boiloff, but at cruise altitude it would result in a pressure differential, tending to burst the tanks, of about 14 psi. Conventional wings can accommodate an internal pressure of only about 4 to 6 psi. While modifying conventional wings and tanks to withstand a 14-psi pressure differential can be expected to yield significant weight penalties, it may be possible to design for differentials somewhat higher than 4 to 6 psi with only small penalties. Such an increase in capability could be used to advantage.

Another technique is the one already mentioned as a solution to the ground-heating problem. If the fuel is sufficiently subcooled, its vapor pressure can be lowered until little or no boiloff occurs in flight. The combined effect of tank pressure and degree of initial subcooling on passenger capacity is shown in figure 10. As just discussed, higher tank pressure appears beneficial, but the data shown do not account for the corresponding penalties in wing and tank weight. The left segments of each curve represent situations where boiloff occurs as tank pressure is reduced during flight from the initial 14.7 psia at takeoff to the indicated final value at altitude. (The small penalty shown for the 14.7-psia case results from heat leaks into the tanks.) With greater amounts of subcooling, the boiloff is reduced and finally is eliminated entirely. The right segments of the curves are regions where there is no boiloff; more subcooling in this region yields small gains corresponding to a lessened need for insulation against heat leaks.

The figure shows that if a tank pressure of 4 psia at altitude is maintained, boiloff can be entirely eliminated if the fuel is subcooled by 33° F (retaining the optimum thickness of insulation). Subcooling should add little to the cost of liquid methane and so appears to be an attractive solution to the problem.

With a vapor pressure of the subcooled methane being loaded into the airplane of the order of 4 psia, it will be necessary to pressurize the tanks by some other gas to 14.7 psia in order to prevent their crushing while on the ground and at low altitudes. The choice of a suitable pressurant is not easy. For example, nitrogen is highly soluble (10 to 15 percent by weight) in 25° F subcooled methane. This could be prevented by development of a flexible separating membrane between the gas and the methane.

Hydrogen gas would be an acceptably insoluble pressurant but probably must be rejected on safety grounds. Helium is also very insoluble and has no safety problem. The only objection here is the question of availability. With an estimated usage of some 30 pounds per flight, the annual consumption of the SST fleet would equal this country's present total rate of consumption. A possible counterargument is that the natural gas from which the methane is obtained usually contains a small amount of helium, which is normally not recovered. Since this helium would otherwise be wasted, it could be separated during the liquefaction process and employed by the airplane.

The remaining critical point in the SST flight path that was pointed out in figure 14 is the boiloff problem during cruise, when aerodynamic heating of the airplane causes increased heat leaks into the tanks. This boiloff can be controlled by insulation. As shown at the left in figure 11, there is an optimum weight of insulation that results in minimum total penalty in insulation plus boiloff. The right side of the figure shows that a much smaller penalty is incurred if the fairly small amount of boiloff during cruise is pumped into the engines. In this case, the fuel-control system must meter methane coming to the engine in both the liquid and vapor forms.

Figure 12 summarizes the increased fuel-system weights due to changing to methane that were assumed in the previous airplane performance calculations. Fiberglass insulation was used to control heat leaks, with a titanium cover to separate and bear the weight of the fuel. Heating wires are indicated to avoid ground icing; a vapor pump is employed during cruise; the fuel is assumed to be sufficiently subcooled to eliminate all boiloff during climb even after some warming during ground holds. (The weight of the helium pressurizing system does not appear in Fig. 12, as it is estimated to be no heavier than the nitrogen pressurizing system that it replaces on the reference JP-fueled airplane.)

A final remark concerning fuel systems is that liquid methane should be a very clean fuel, with no difficulties due to fouling of heat exchangers, clogging of injectors, etc.

Combustors. - Methane appears to be a highly desirable fuel with respect to combustion. Because of its gaseous nature when injected, shorter and/or more efficient combustors could be designed. This would be particularly true for afterburners or duct burners, as suggested by the empirical curve shown in Fig. 13 for propane gas.[4] A further benefit results from the high percentage of hydrogen (and corresponding low percentage of carbon) in the methane fuel, which leads to flames with low luminosity. The experimental data[5,6] shown in Fig. 14 indicate that, as the hydrogen content of hydrocarbon fuels increases, the radiant heat flux and average liner temperature decrease. The trend strongly suggests that the use of methane fuel (with its 25-percent hydrogen content) may yield significant benefits in liner durability for the same gas temperature. Similar benefits obtain for the first turbine-stator row.

Turbine cooling. - The benefits of applying the good heat-sink capacity of methane for better cooling of the turbine blades have already been mentioned. A fairly straightforward technique to accomplish this is to chill the compressor bleed air on its way to the turbine by using a heat exchanger (Fig. 15). The weight of this heat exchanger, which is small enough to incorporate into the engine, was included in the previous calculations. Figure 16 shows an alternative technique in which the methane cools the blades directly, and no air needs to be bled from the compressor. Engine efficiency is improved thereby, but the developmental problems appear more severe in this case.

Safety. - A cursory study reveals no major safety hazards associated with methane. The higher ignition temperature of methane reduces the possibility of ignition by friction sparks and hot metal surfaces in the event of a crash. Liquid methane has less tendency to accumulate in pools from small leaks since it evaporates readily; after slight warming, the vapor becomes lighter than air. This reduces the likelihood of ignition and also the extent of damage in the event of fire. During fuel loading, the danger of building up an electrostatic charge that might ignite the fuel is less with methane. If a fire does actually start, its severity is no worse than for JP fuel, becuase of the low emissivity of a methane flame. (A discussion of fire hazards is presented in Ref. 7.)

SPECIAL APPLICATIONS FOR METHANE

Because methane can be so easily gasified, can be heated to high temperatures without significant decomposition, and has a high specific heat, it makes a good thermodynamic working fluid. Some examples of the potentialities offered thereby are briefly outlined in this section.

Inlet Injection

The concept of adding a cryogenic fluid to the supersonic airstream approaching the engine inlet has been considered at various times in the past. The act of cooling the airstream in this fashion has the dual virtues of increasing the engine airflow and increasing the effective inlet pressure recovery. This, then, represents an alternative means for utilizing the heat-sink capacity of methane.

Some preliminary efforts were attempted at Lewis in 1955 to demonstrate this concept by using liquid nitrogen and ammonia, but with little success.[8] Nevertheless, the possibility of some overall gain by using methane cannot yet be ruled out.

Engine Cycles

Several of the exotic systems using hydrogen fuel that have been discussed in the classified literature could also be employed with methane to replace the conventional turbojet or turbofan. The two systems described below, however, represent only modifications to the conventional cycles. (Results are taken from unpublished data by B. A. Miller of NASA-Lewis.)

Fuel heating. - The low temperature of liquid methane aids in providing its desirably high heat-sink capacity. On the other hand, this low temperature corresponds to a loss in fuel-heating value, compared with gaseous methane at room temperature. (The previous engine calculations were based on the use of liquid methane.) If the full cooling capacity of the liquid is not required within the engine, some improvement in effective heating value and, hence, in specific impulse can be obtained by heating the methane prior to its reaching the engine. To be effective, the heat source must be external to the propulsion system or heat otherwise lost from the propulsion system. (For example, the methane heating that occurs due to turbine or oil cooling does not improve engine specific impulse.) Some heat is added by the cabin air-conditioning system. More heat can be picked up from the hot parts of the airframe structure, particularly the wing leading edges. If the fuel temperature is thus raised by nonengine sources to 540° F, the specific impulse of the engines can be raised by 3 percent.

Fuel expansion. - Rather than simply burning the warmed methane as in the previous example, the vapor could be first expanded through a small turbine to generate shaft power. This shaft power might be fed into the primary compressor or drive auxiliary systems usually powered by the primary turbine. In either event, an increase in specific impulse of the main engine cycle is obtained. As shown in Fig. 17, a total improvement of about 5 percent is possible.

Gains of this magnitude are small, but not negligible. Of course, the associated penalties in weight and complexity would have to be carefully studied.

Boundary-Layer Modification

It was previously suggested that it might be desirable to circulate the methane near the wing leading edges in order to pick up thermal energy.

The consequent cooling of the wing might have a beneficial effect on airplane drag if the laminar-to-turbulent boundary-layer transition were delayed.

A more direct way to lower the drag is to replace the normally occurring boundary layer by an artificial one of methane vapor. (The spontaneous ignition temperature is about 1200° F, well above the air-stagnation temperature at Mach 3.) As shown in Fig. 18, the reduction in drag may be interpreted as an increase in engine specific impulse (unpublished data by R. L. Luidens and M. D. Shovlin of Lewis.) The illustrated benefit of raising the temperature of the methane is the result of a reduction in gas density. To achieve any real benefit, it is necessary to limit the methane used to no more than that required by the engines and to recover all the methane for later injection into the engine. Conceptually, this can be accomplished by an arrangement such as that depicted in Fig. 19. The complex analysis of boundary-layer behavior required to determine how much methane is needed, mixing rates, etc., has not yet been performed.

CONCLUDING REMARKS

Methane fuel is superior to JP fuel in terms of heating value, cooling capacity, and possibly cost. Despite the low density, these favorable attributes are estimated to improve the payload and reduce the D.O.C. of a representative supersonic transport by approximately 30 percent. Unusual engine cycles might lead to still further improvements.

Redesign of turbojet or turbofan engines to utilize methane fuel undoubtedly would require specific development effort, but the problems do not appear to be major ones. In some respects the engines may be easier to develop for methane than for JP fuel.

The more serious problems are probably connected with the fuel systems external to the engine proper. On the airplane, a new technology of insulations, pumps, lines, and controls, heat exchangers, perhaps materials, etc., is required. On the ground, new fueling systems must be provided at all major airports. Even the process of loading the liquid methane into the airplane presents unique difficulties, especially if the fuel is subcooled.

Obviously, much more detailed and extensive work must be carried out before the potential of methane can be confirmed and such a drastic change in airplane design implemented. Presuming that the potential can be substantiated, it is conceivable that methane could be put into use on a step-by-step basis. For example, modest changes in already built aircraft might permit switching to methane fuel. At a later date, new high-temperature engines could be retrofitted. And finally, completely new vehicles could ultimately be designed to take maximum advantage of methane.

The substitution of an entirely new type of fuel for ordinary commercial operation is not to be contemplated lightly. However, the benefits of using methane for the SST and possibly other airplanes are so great that a large-scale program of analysis and research to substantiate the concept seems to be amply justified.

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TABLE I. - PROPERTIES OF FUELS

Fuel	Heat of combustion, Btu/lb	Heat-sink limit temperature, °F	Heat sink, Btu/lb	Density, lb/ft^3	Boiling point, °F	Freezing point, °F
Methane	21,500	[a]1000	1100	[b]26.5	-259	-296
JP (regular)	18,600	375	165	50	300	-65
Ethane	20,420	950	750	[b]33.0	-128	-298
Propane	19,930	850	700	[b]36.5	-44	-306
JP (gold plated)	18,700	700	365	50	300	-65
Hydrogen	51,570	[a]1000	4900	[b]4.3	-423	-435
Nitrogen	------	-----	----	[b]50.5	-321	-346
Oxygen	------	-----	----	[b]71.5	-297	-362

[a]Fuel limit, ~1200° F for methane; no limit for hydrogen.

[b]Density at normal boiling point.

TABLE II. - FUEL PROPERTIES AT 1 ATMOSPHERE

Property	Fuel	
	Methane	JP[a]
Heat of vaporization, Btu/lb	219	120
Heat of fusion, Btu/lb	25	-------
Specific heat, Btu/(lb)(^{o}F):		
Liquid	[b]0.82	0.47
Vapor	[c]0.49	0.6
Thermal conductivity, Btu/(hr)(ft)(^{o}F):		
Liquid	[b]0.11	0.08
Vapor	[c]0.015	0.015
Surface tension, dynes/cm	[b]14	22
Viscosity of liquid, centistokes	0.28	1.5
Spontaneous ignition temperature, ^{o}F	1200	480
Lean flammable limit, fuel-air ratio	0.028	0.035
Rich flammable limit, fuel-air ratio	0.095	0.27
Maximum flame velocity, cm/sec	37	38
Gas solubility, percent by weight:		
Nitrogen	[d]~10	0.02
Helium	[d]~0.003	0.00005

[a]Liquid at 60° F or vapor at 500° F.

[b]At normal boiling point, -259° F.

[c]At -10° F.

[d]For methane subcooled 25° F.

TABLE III. - PRODUCTION AND RESERVES

OF NATURAL GAS (1961)

[Estimated consumption of 400 SST'S, 2×10^{12} cu ft.]

Source	Reserves		Consumption (1961)
	Proved	Ultimate	
[illegible] Gas, cu ft			
North America	321×10^{12}	1000×10^{12}	14.6×10^{12}
Middle East	178		1.1
Iron Curtain	83		2.6
Africa	55		.1
South America	45		1.7
Far East	20		.2
Europe	19		.6
Total	721×10^{12}	6000×10^{12}	20.9×10^{12}

E-3447

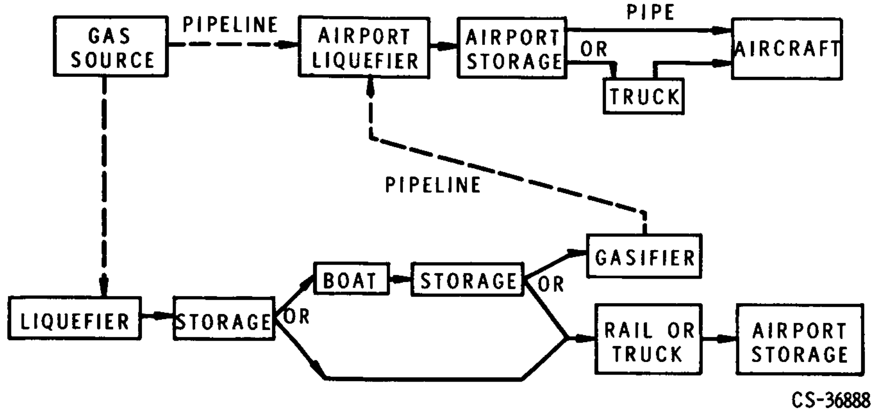

FIGURE 1. - LIQUID-METHANE DISTRIBUTION SYSTEM.

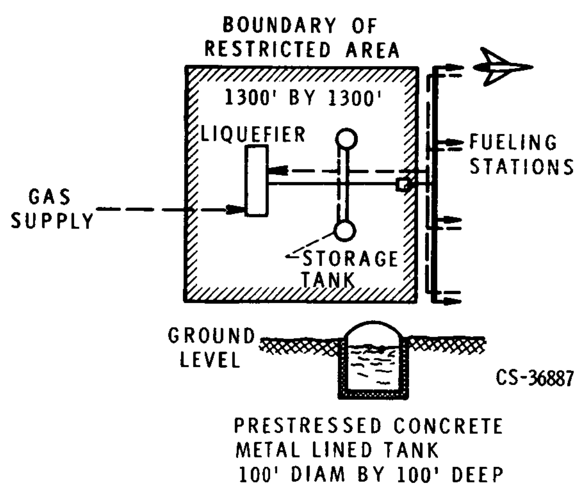

FIGURE 2. - AIRPORT LIQUID-METHANE FACILITY. LIQUEFIER CAPACITY: GASEOUS METHANE, 10^6 POUNDS PER DAY; LIQUID METHANE, SUFFICIENT TO RELIQUEFY VENT AND BOILOFF GAS.

E-3417

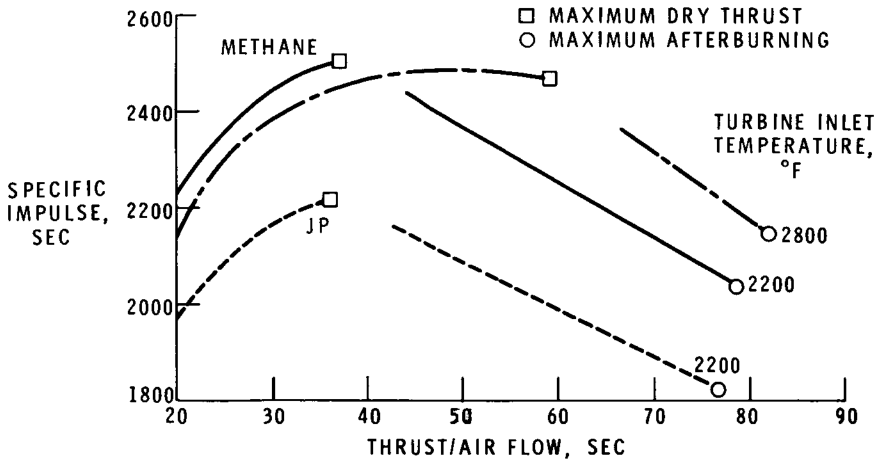

FIGURE 3. - TURBOJET ENGINE PERFORMANCE. CRUISE MACH NUMBER, 3.0.

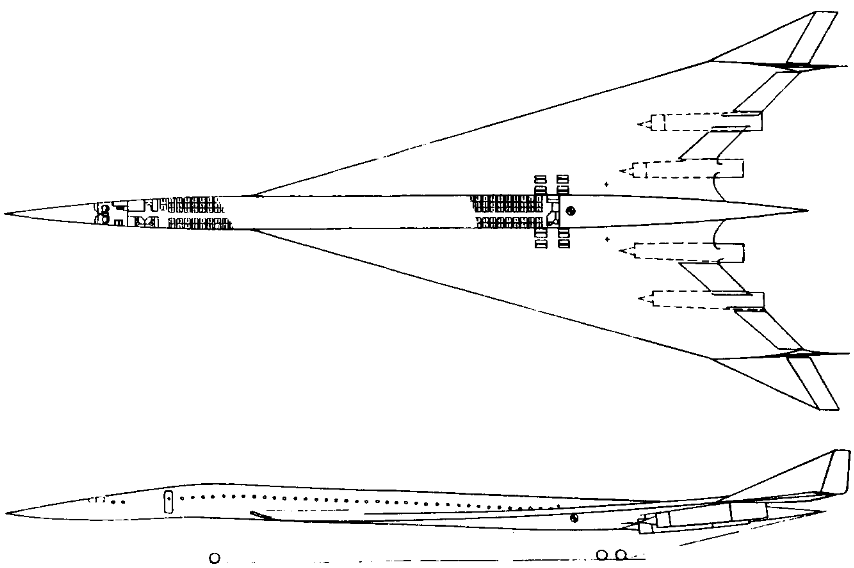

FIGURE 4. - TYPICAL SST CONFIGURATION.

E-3417

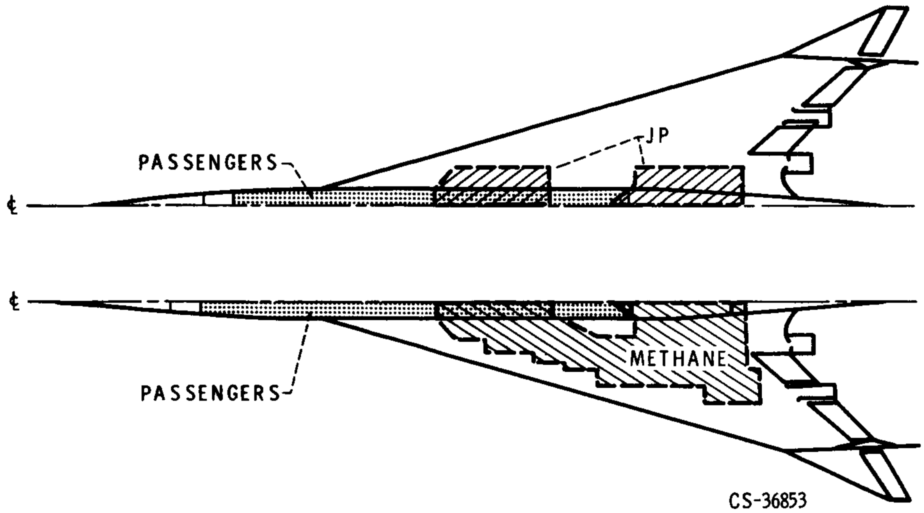

FIGURE 5. - FUEL STORAGE.

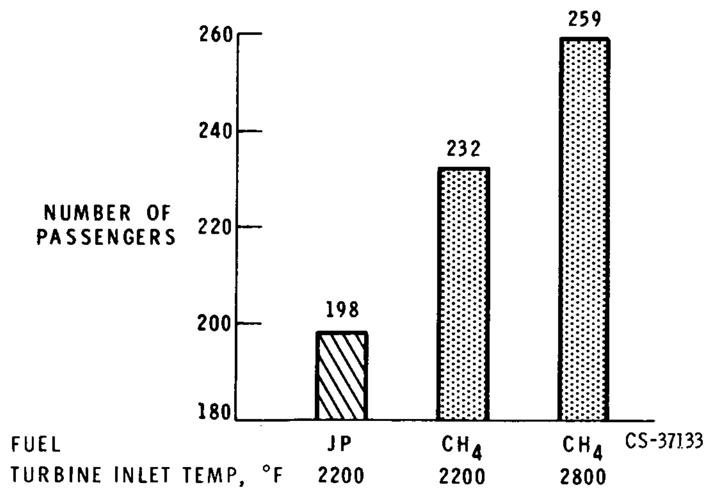

FIGURE 6. - METHANE BENEFITS PAYLOAD.

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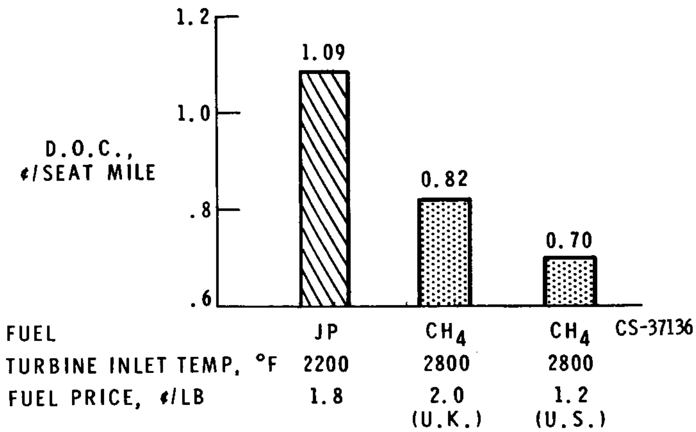


FIGURE 7. - METHANE COULD LOWER DIRECT OPERATING COST.

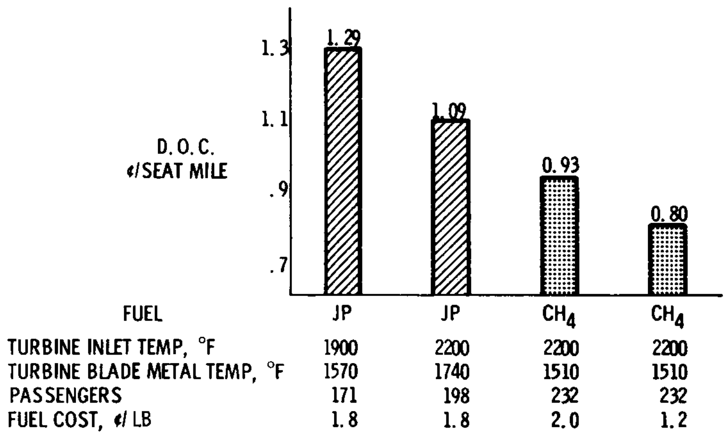


FIGURE 8. - ALTERNATIVE BENEFIT OF HEAT-SINK CAPACITY. WING LOADING, 50 POUNDS PER SQUARE FOOT.

E-3447

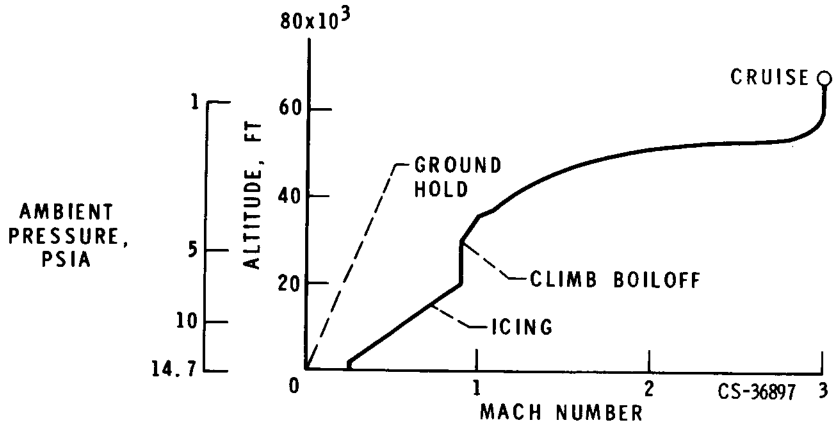


FIGURE 9. - TYPICAL SST FLIGHT PLAN.

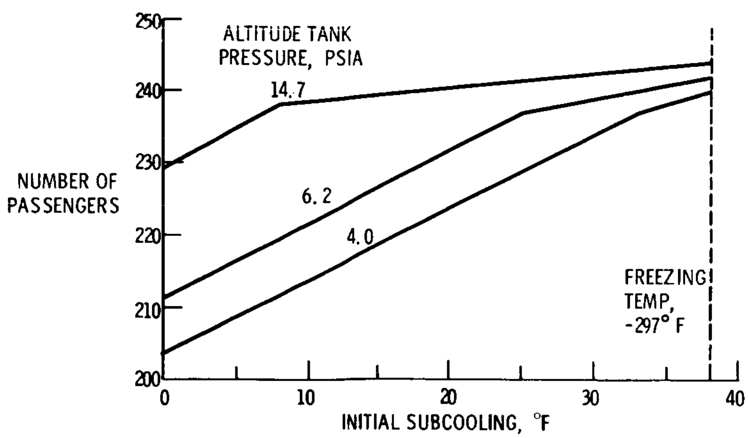


FIGURE 10. - BENEFIT OF SUBCOOLING METHANE.

E-3447

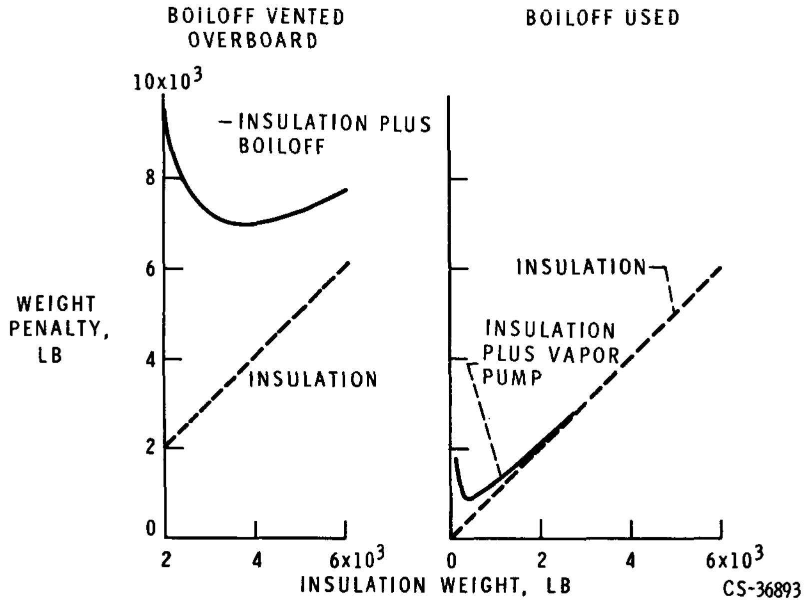
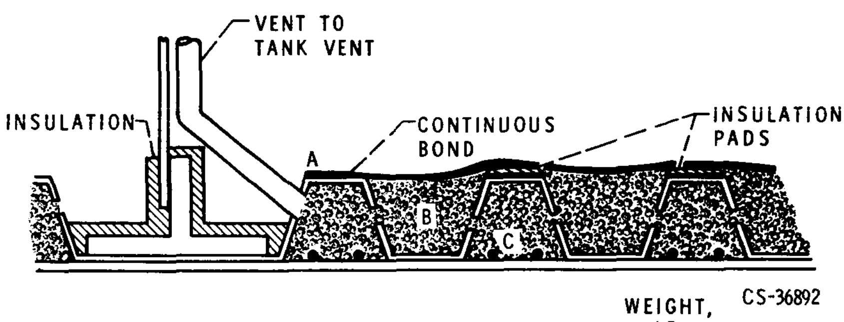


FIGURE 11. - FUEL INSULATION FOR CRUISE.



		WEIGHT, LB
A	- .010 Ti COVER (NONSTRUCTURAL)	1200
B	- FIBERGLASS INSULATION	1200
C	- NICHROME HEATING WIRES	300
D	- CRUISE VAPOR PUMP	300
E	- FUEL SYSTEM HARDWARE INCREASE	500
	TOTAL	3500

FIGURE 12. - METHANE SYSTEM WEIGHT PENALTY.

E-3447

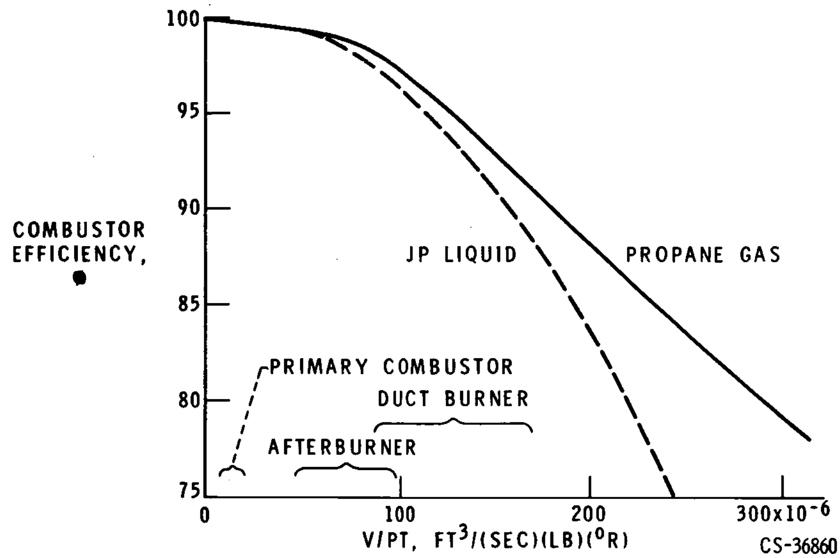


FIGURE 13. - COMBUSTOR BENEFITS.

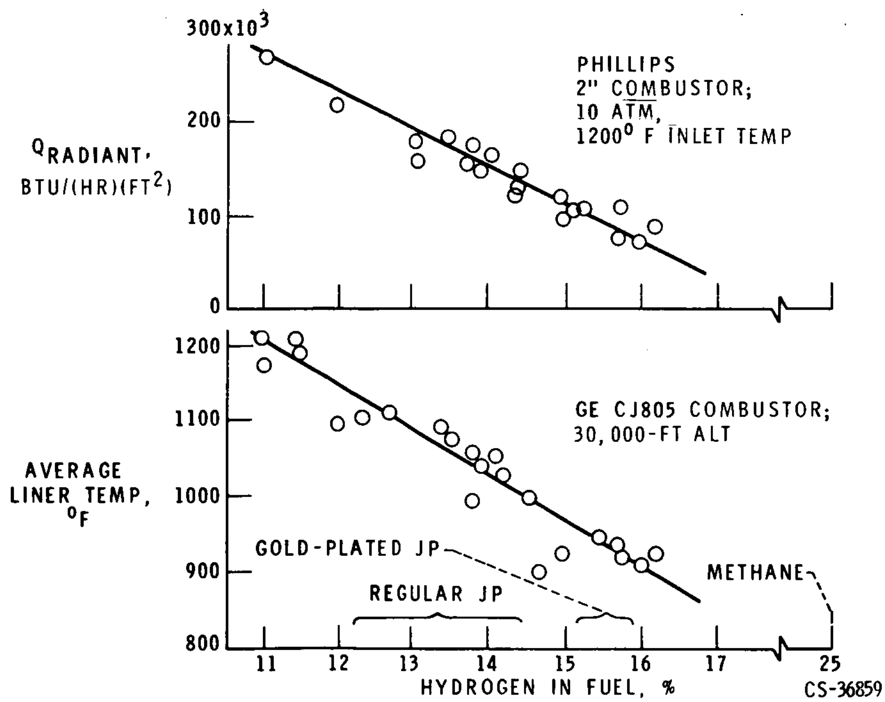


FIGURE 14. - RADIANT HEAT-TRANSFER EXPERIMENTS.

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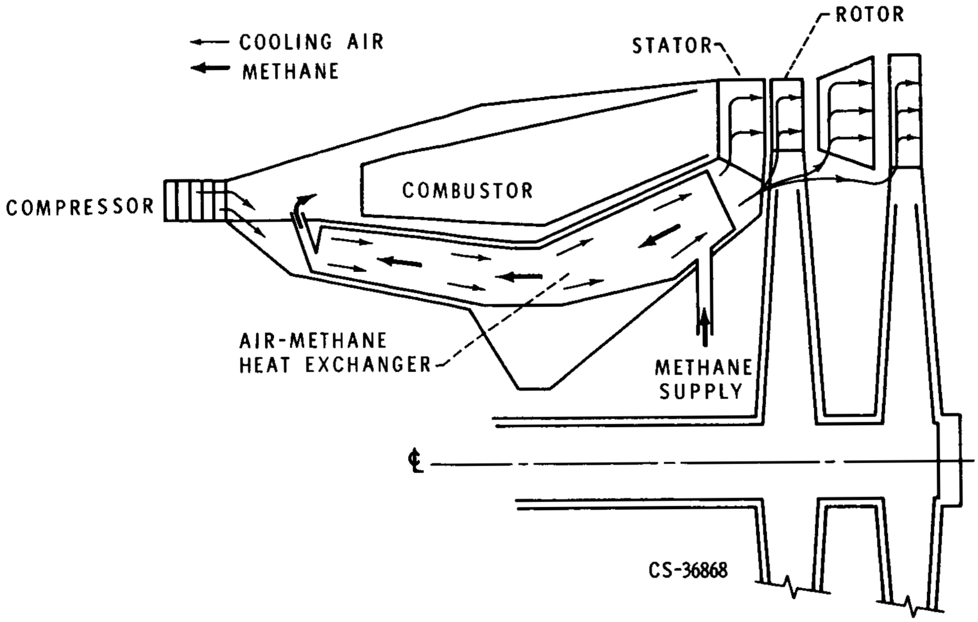

FIGURE 15. - COOLING AIR REFRIGERATION WITH METHANE.

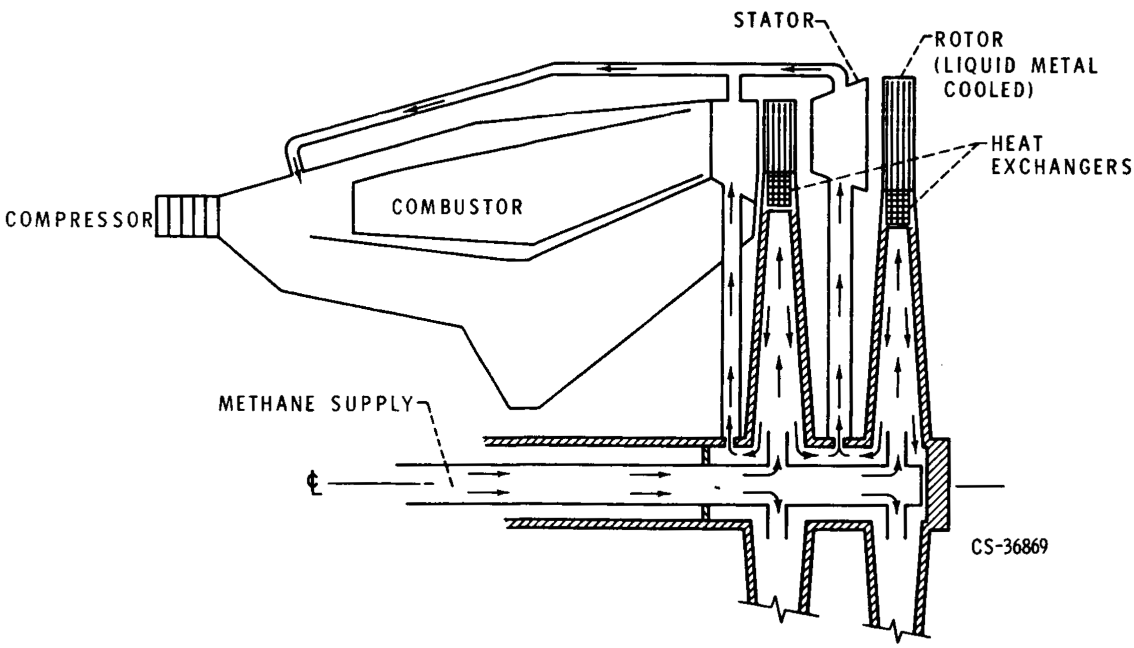

FIGURE 16. - ELIMINATION OF COOLING AIR FOR TURBINE COOLING.

E-3447

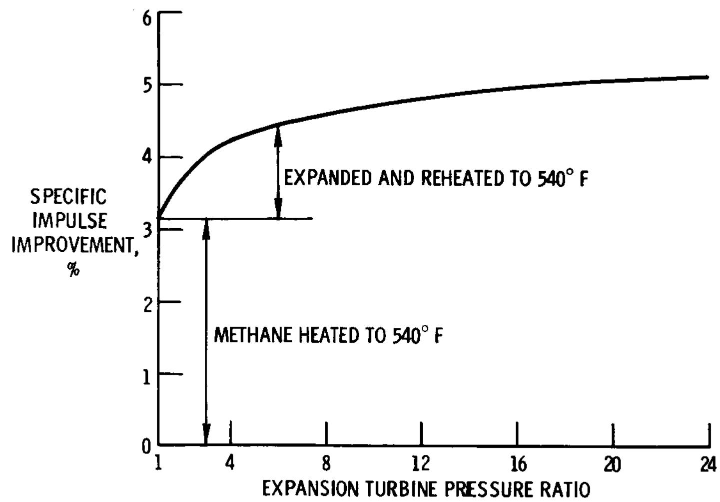

FIGURE 17. - BENEFIT OF SPECIAL ENGINE CYCLES.

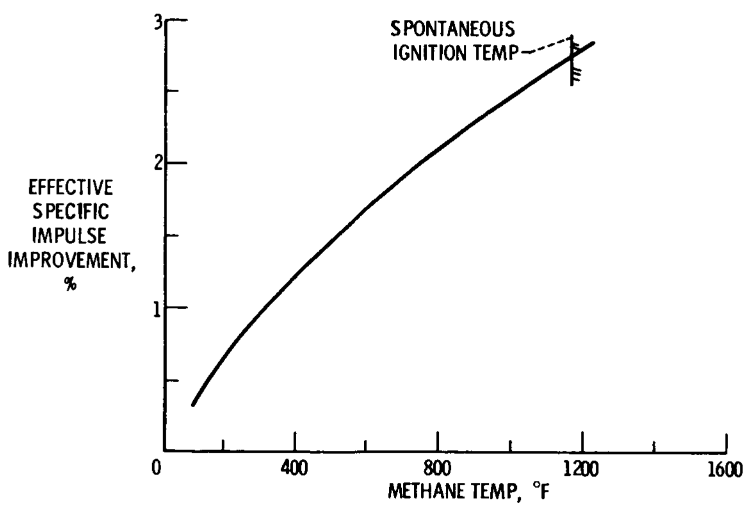

FIGURE 18. - METHANE INJECTION REDUCES SKIN FRICTION.

E-3417

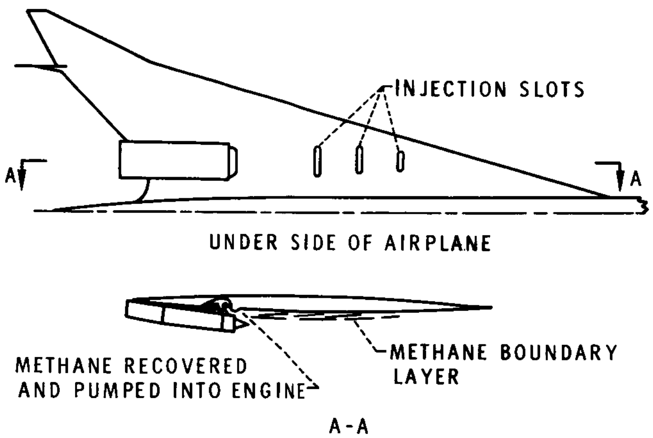

FIGURE 19. - METHANE INJECTION IN BOUNDARY LAYER AND RECOVERY.